MEASUREMENTS AND CALCULATIONS
OF SHIP RESISTANCE IN WAVES--
PART II.

by

O. J. Sibul

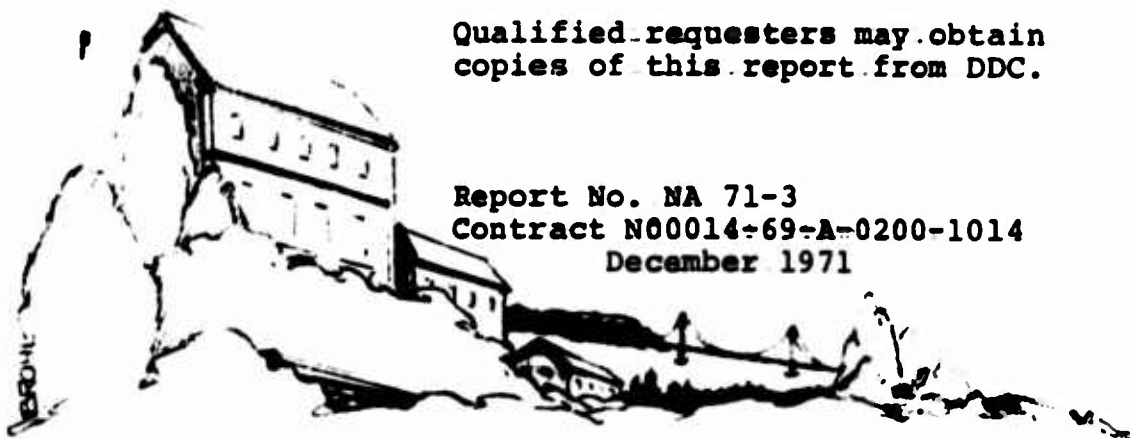Qualified requesters may obtain
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13. ABSTRACT

This report is supplementary to Reference 1. It is recommended that Reference 1 be read before this report is studied.

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under the Naval Ship Systems
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Nomenclature

A Wave amplitude $= \frac{H}{2}$

B Beam of the ship in ft

D Draft of the ship in ft

$\overline{F}_x$ Average drift force

F_N Froude number: $\dfrac{V}{\sqrt{gL}}$

g Acceleration due to gravity

H Wave height

$H_{sign} = H_{1/3}$ Significant wave height, i.e. the average of the 1/3 of the highest waves.

K Wave number $= \dfrac{2\pi}{\lambda}$

K_w Added resistance coefficient

L Length of the ship on waterline in ft

R_a The added resistance due to a wave component. It is the difference between the resistance in waves and in calm water.

R_{ta} The total added resistance in a spectrum of waves.

$S(\omega)$ Spectral density

$S(\omega_e)$ Spectral density of wave encounter

T	Wave period in seconds
V	Ship speed in knots
v	Ship speed in ft/sec
Δ	Weight of displacement in lbs
λ	Wave length in ft
ρ	Density of water
ω	Circular frequency $\dfrac{2\pi}{T}$
ω_e	Circular frequency of encounter

I.   Introduction

This is an extension of the previous report "Measurements
and Calculations of Ship Resistance in Waves", Report No. NA-71-2
[Reference 1]. Here data are given for an additional model. The
methods of measurements as well as most of the discussion and
conclusions are valid for this report as well. It is recommended
that Reference 1 be read before this report is studied.

II.   The Model

The experiments were performed with a model having a block
coefficient $C_B = 0.49$, and a   length-beam ratio of 8.6. The model
was 5-feet long and made of wood. Total weight of the model was
19.38 pounds. This weight includes the portion of the dynamometer
supported by the model. The radius of gyration was adjusted to be
25 percent of the length. The center of gravity was 0.22 feet
above the keel, and 0.06 feet aft of the centerline. In order to
stimulate turbulence, the model was fitted with a row of studs
3/32 inch in diameter and 1/16 inch high, one-half inch apart at
Station 1.   Turbulence stimulation was necessary because calm-
water resistance was measured consecutively with wave tests. No
correction for studs has been applied to the results as reported here.

III.   Constant Thrust and Constant Velocity
Methods of Towing

The results of the comparison for constant-thrust and constant-
velocity methods of towing in regular waves are given in Figure 1 for
Froude number equal to 0.25, and in Figure 2 for Froude number 0.35.
About 10 different wave lengths were used for each set of experi-
ments to achieve a good definition of the response operator $\frac{R_d}{AH^2}$.

The wave heights were adjusted in each case to give reciprocal wave steepness $\lambda/H = 40$. The results for constant-thrust tests as given for comparison in Figures 1 and 2 were taken from Reference 3.

There are some differences in results. The peaks of the curves for constant-velocity towing are somewhat narrower, and the left side of the curve is shifted towards the higher frequencies. However, if we consider also the results as reported for Series 60 models in Reference 1, Figures 1-4, then it is rather hard to establish a trend. Differences could have been caused by a possible error in constant-thrust measuremenets. Constant-thrust measurements are very hard to perform. Because of the friction between the subcarriage and the main carriage, it takes a certain force to get the subcarriage rolling, with a resultant dead-span. This means a range of uncertainty for the exact value of the resistance. Another possible source of error in constant-thrust measurements is the fact that calm-water resistance was measured in separate sets of experiments, and not in consecutive runs with the wave tests, as was the case in the recent set of tests for constant velocity.

At the present time, it is still concluded that either method can be used to measure the added resistance in waves. The constant-velocity method is recommended because it is much simpler to apply, and the results are more accurate and reliable.

IV.   The Relationship Between the Added
Resistance and the Wave Height

Present applications of the spectral method require that the added resistance be proportional to the second power of the wave height for a given wave length. It is necessary to determine for which ranges of hull forms, speeds, frequencies, etc. (important for a naval architect) the second-power relationship can be used with sufficient accuracy to yield results which are acceptable from the engineering point of view. Extensive experiments were made by the constant-velocity method of towing to study the relationship between the wave height and the added resistance. The results are plotted

in logarithmic scale in Figure 1. This figure demonstrates that the added resistance for the entire range of wave heights cannot be represented by a single straight line. This is the same phenomenon found in earlier experiments and reported in References 1 and 3. It is interesting to note that the data for waves steeper then approximately 1:50 can be represented rather well by a line with 1:2 slope indicating that the added resistance is proportional to wave height squared in this range. For lower waves the line has a 1:1.68 slope. This is similar to the results for Series 60 models and has been discussed in Reference 1. The same recommendation that the spectral method should be accepted to predict the added resistance in waves still stands. The response operator should be derived from tests in regular waves with the wave steepness $\lambda/H < 50$. An approximate value of $\lambda/H = 40$ is recommended.

V. <u>Horizontal Dynamic Force</u>

The total horizontal force acting on a ship in a seaway can be separated in two parts. One component is a net horizontal force that usually increases the average ship resistance in waves. This force has been the main subject of the report because it represents an added resistance and power has to be provided to maintain the speed.

The second part is the horizontal component of the force caused by the orbital velocities in waves. It is a dynamic force that changes cyclically between negative and positive values. It is the primary force and its amplitude could be 50 times larger than the average added resistance. The force integrates to zero over a long time period and is not supposed to affect the power requirements of the ship if an average speed has to be maintained. However, it is useful to know the magnitude of this force because it can load the propeller and the propulsion machinery. It is also important when a ship has to be anchored in waves.

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The force was measured at zero forward speed for five different wave lengths and six different wave heights for each length. The results are given in Figures 4 and 5. The amplitude of the force F_H is plotted in logarithmic scale in Figure 4. It is proportional to the wave height except for very steep waves which are pointed out in Figure 4.

The horizontal force coefficient is given as:

$$\frac{F_H}{\rho g K A B^2 L}$$

ρ is the density of water

g the acceleration of gravity

$K = \frac{2\pi}{\lambda}$ is the wave number

$A = H/2$ is the wave amplitude

B the beam of the ship

L the length of the ship

It is plotted in Figure 5 as a function of wave length λ . It is apparent also from this Figure that the horizontal component of the dynamic force is proportional to the wave height, except for very steep waves where smaller variations can be observed.

VI. Response Operator

We have concluded that the spectral method can be used to estimate the added resistance of a ship in various sea states. The necessary response operator can be calculated theoretically or derived experimentally in uniform waves.

A considerable amount of data have been collected over the years using the constant-thrust method. These data have been rearranged and are given as Figure 6, and tabulated in Tables I and II. They are arranged so that they can be used as computer input to calculate the added resistance in irregular waves for any desired scale. K_w is the added resistance coefficient so that:

$$R_a = K_w \rho g \left(\frac{H}{2}\right)^2 \frac{B^2}{L}$$

R_a is the added resistance in a wave component. $\omega_e \sqrt{\frac{L}{2\pi g}}$ is the dimensionless frequency, with ω_e being the circular frequency of encounter.

The spectral method is represented by the following formula:

$$R_{ta} = 2 \int_o^\infty S(\omega_e) \left[\frac{R_a}{(H/2)^2}\right] (\omega_e) d\omega_e$$

R_{ta} is the total added resistance in a spectrum of waves $S(\omega_e)$, which has been corrected for the frequency of encounter ω_e. $\left[\frac{R_a}{(H/2)^2}\right] (\omega_e)$ is the response operator. It can be easily calculated for a desired scale from tabulated values of K_w (Table I). The frequency of encounter is calculated as:

$$\omega_e = \left(\omega_e \sqrt{\frac{L}{2\pi g}}\right) \bigg/ \sqrt{\frac{L}{2\pi g}}$$

$\rho g \, B^2/L$ and $\sqrt{\frac{L}{2\pi g}}$ are constants for a given ship size, and can be easily applied by the computer to the tabulated values.

VII. <u>References</u>

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    "Measurements and Calculations of Ship Resistance in Waves",
    University of California, College of Engineering, Report
    No. NA-71-2, December 1971.

2. Sibul, O. J.

    "Constant Thrust vs. Constant Velocity Method for Resistance
    Measurement in Waves", University of California, College of
    Engineering, Report No. NA-71-1, June 1971.

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    "Ship Resistance in Uniform Waves", University of California,
    Institute of Engineering Research Report No. NA-64-1,
    Berkeley, January 1964.

TABLE I

Added Resistance Coefficient

$\omega_e \sqrt{\dfrac{L}{2\pi g}}$	K_W for a given Froude Number F_N					
	$F_N =$ 0.10	0.15	0.20	0.25	0.30	0.35
0.7	0	0	0	0	0	0
0.8	0.6	0.6	0.6	0.6	0.6	0.6
0.9	1.5	1.5	1.5	1.5	1.5	1.5
1.0	2.1	2.5	2.5	2.5	2.5	2.5
1.1	2.7	3.7	3.8	3.8	3.8	3.8
1.2	3.2	4.5	5.3	5.3	5.3	5.3
1.3	3.6	5.0	6.7	7.5	7.5	7.5
1.4	4.0	5.5	7.7	10.5	10.5	10.5
1.5	4.4	5.8	8.1	11.3	13.9	14.1
1.6	4.7	6.0	8.0	11.0	13.9	16.8
1.7	4.9	6.2	7.8	10.4	12.8	15.2
1.8	5.0	6.1	7.3	9.7	11.8	13.9
1.9	4.6	5.6	6.8	8.8	10.8	12.6
2.0	3.6	5.0	6.1	7.9	9.7	11.3
2.1	2.3	4.1	5.4	6.8	8.6	9.9
2.2	1.3	3.0	4.5	5.7	7.5	8.6
2.3	0.6	1.8	3.5	4.6	6.4	7.4
2.4	0	0.9	2.4	3.5	5.3	6.2
2.5		0.3	1.5	2.5	4.1	5.0
2.6			0.6	1.6	3.0	3.9
2.7				0.7	0.9	2.8
2.8					0.9	1.7
2.9						0.8
3.0						

TABLE II

Location of Maximum Response
for Various Speeds

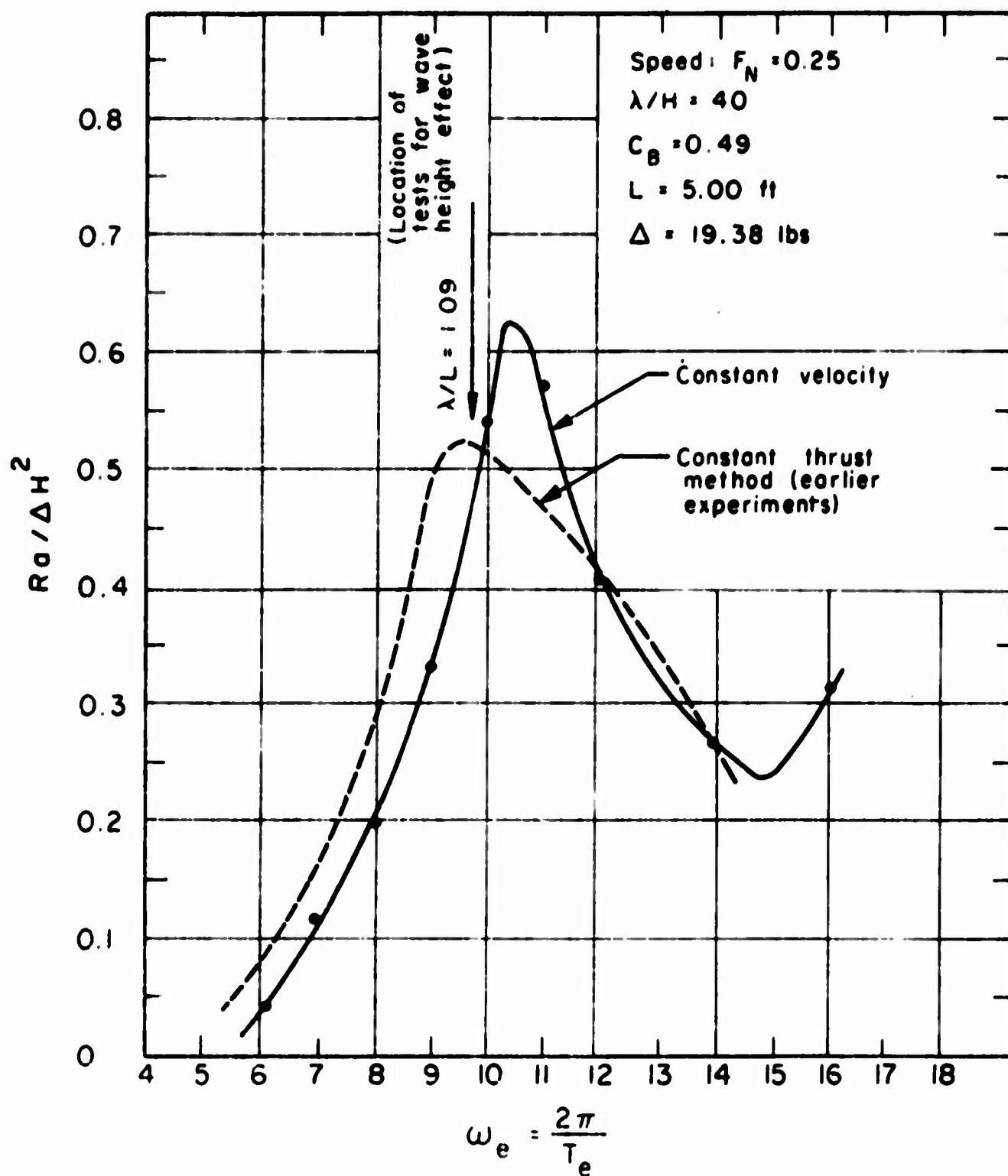| Froude No. F_N	$\omega_e\sqrt{\dfrac{L}{2\pi g}}$ for max. K_w	MAXIMUM K_w
0.10	1.78	5.0
0.15	1.72	6.2
0.20	1.53	8.1
0.25	1.52	11.3
0.30	1.54	14.1
0.35	1.57	17.1

FIG. I   RESPONSE OPERATOR
(CONSTANT VELOCITY TOWING)
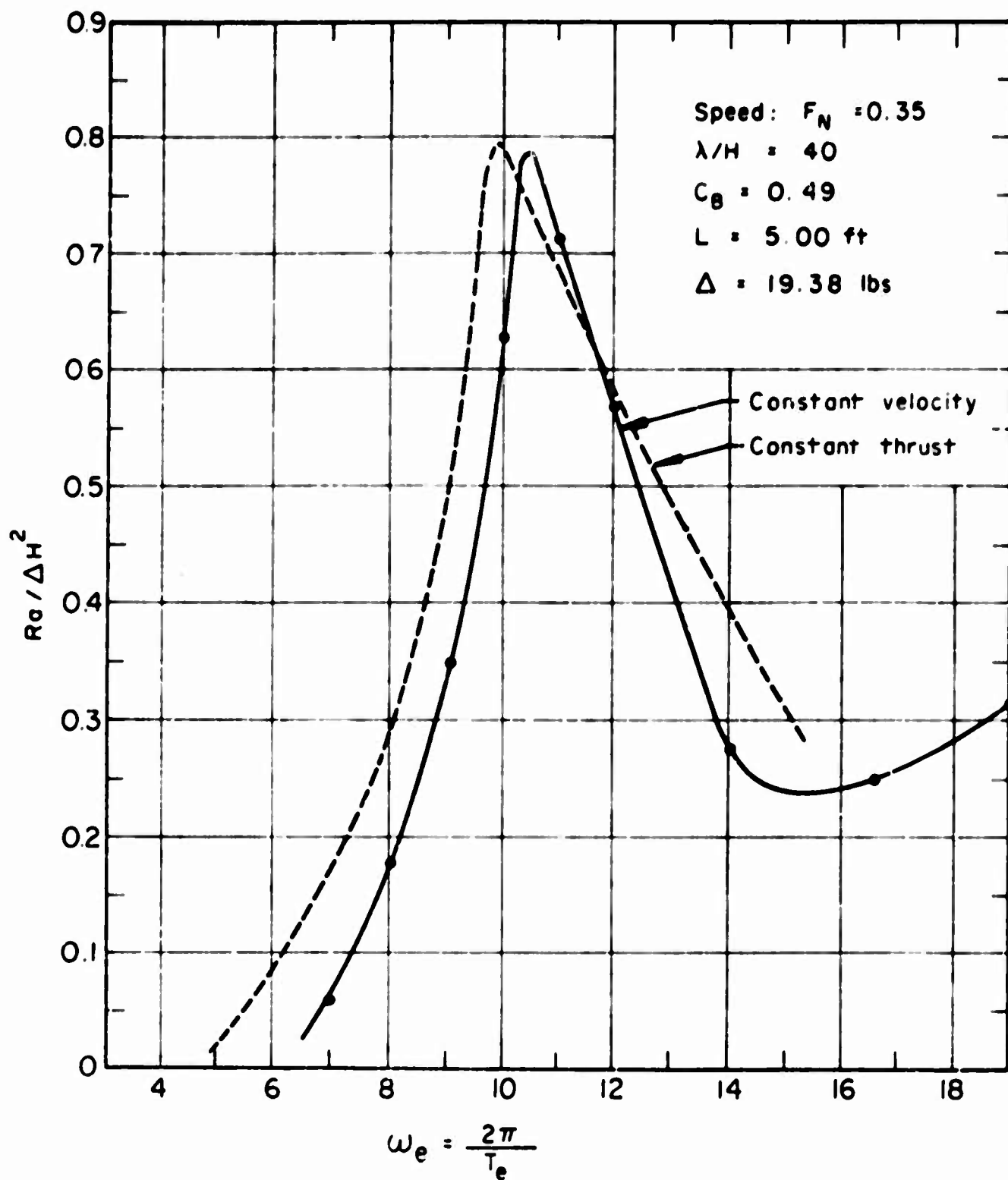
FIG. 2   RESPONSE OPERATOR
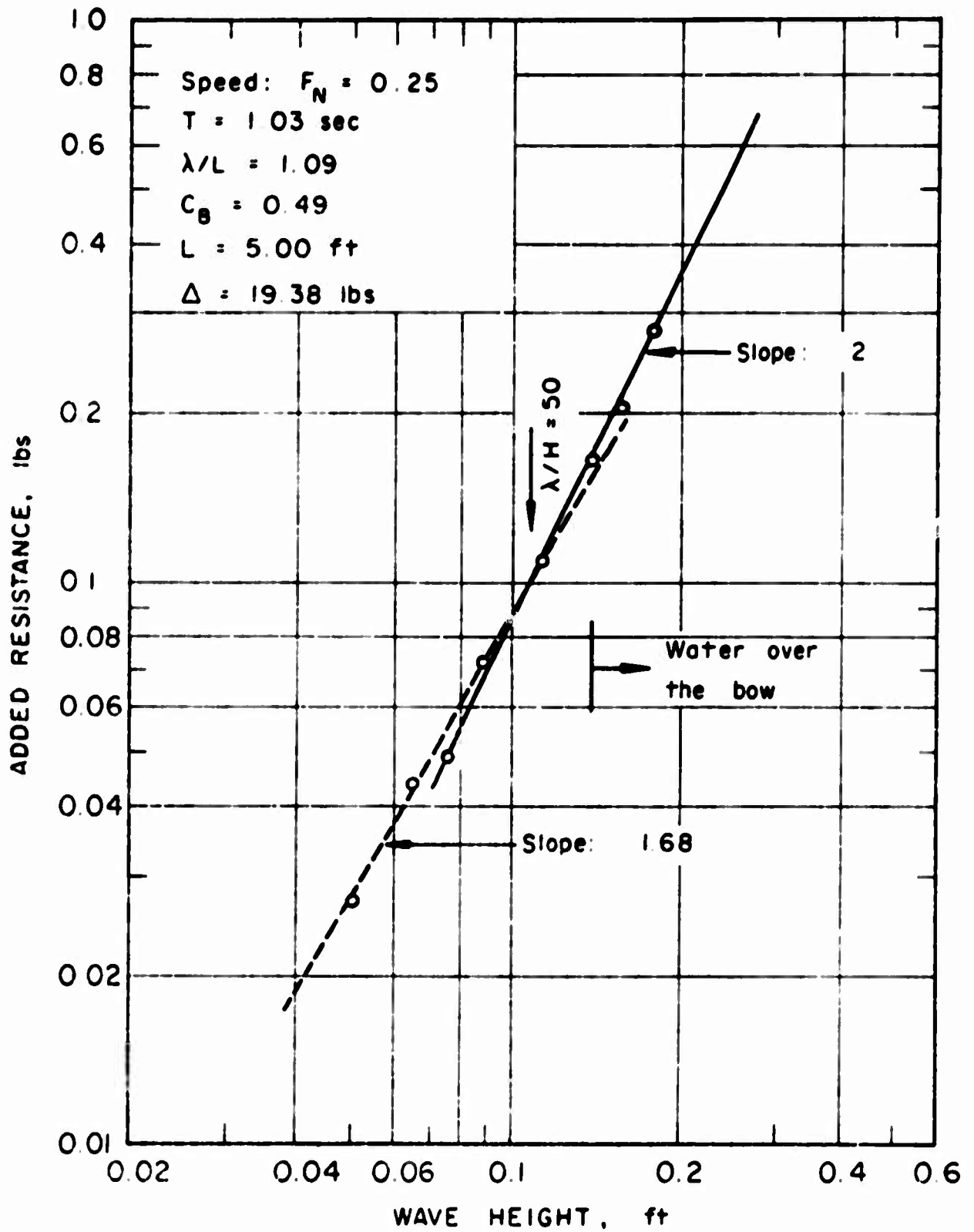CONSTANT VELOCITY TOWING

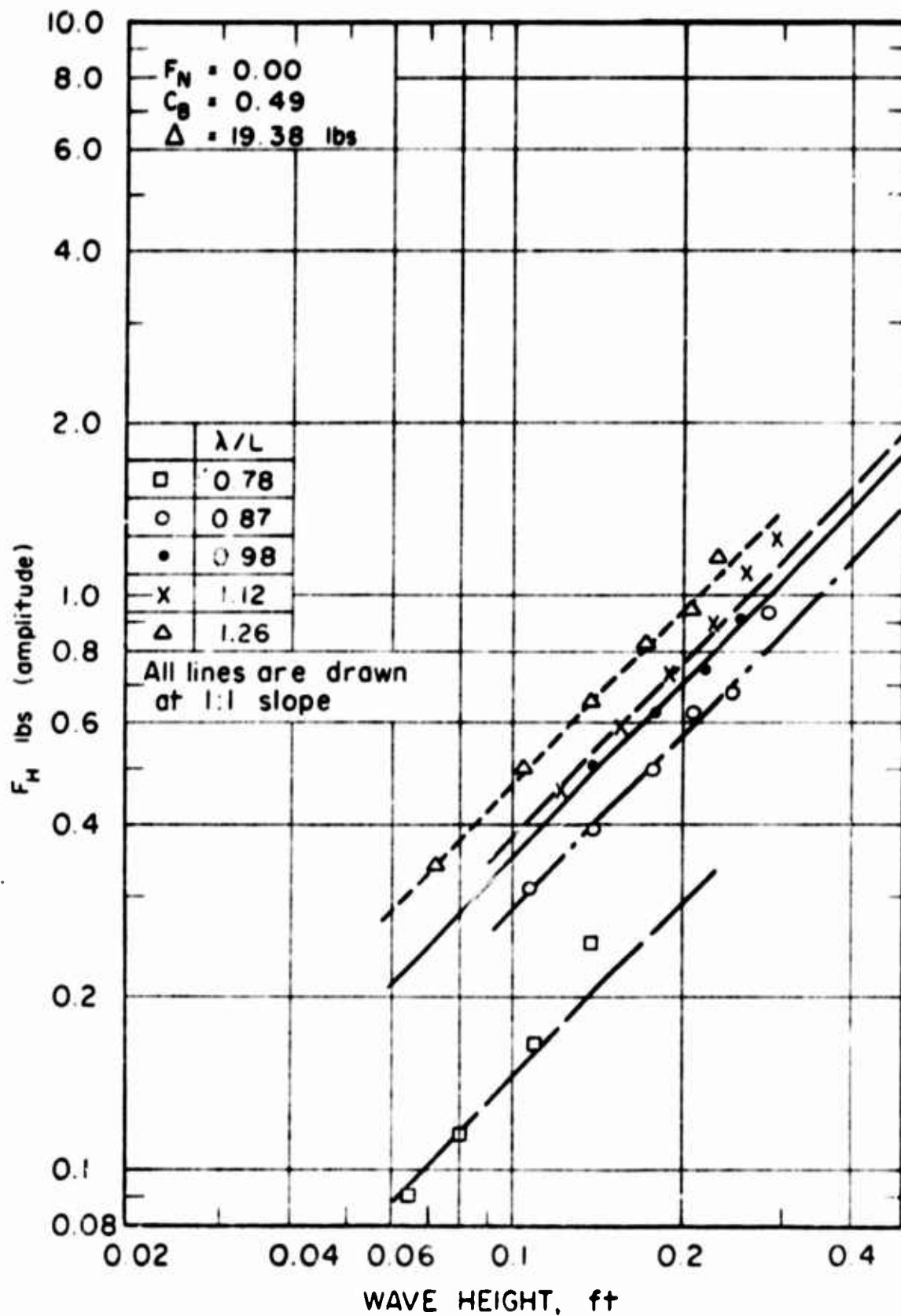FIG. 3 ADDED RESISTANCE AS A FUNCTION OF WAVE HEIGHT

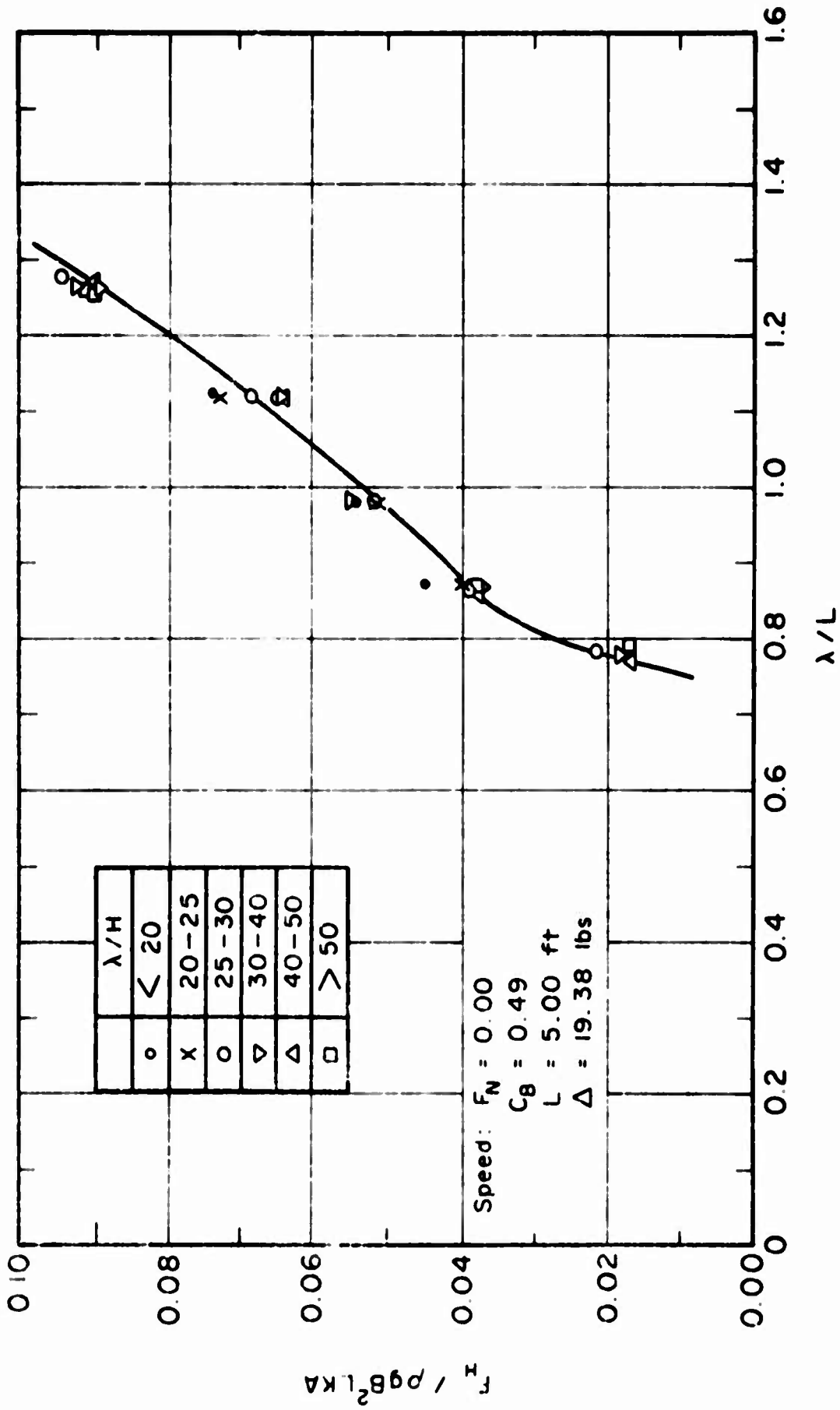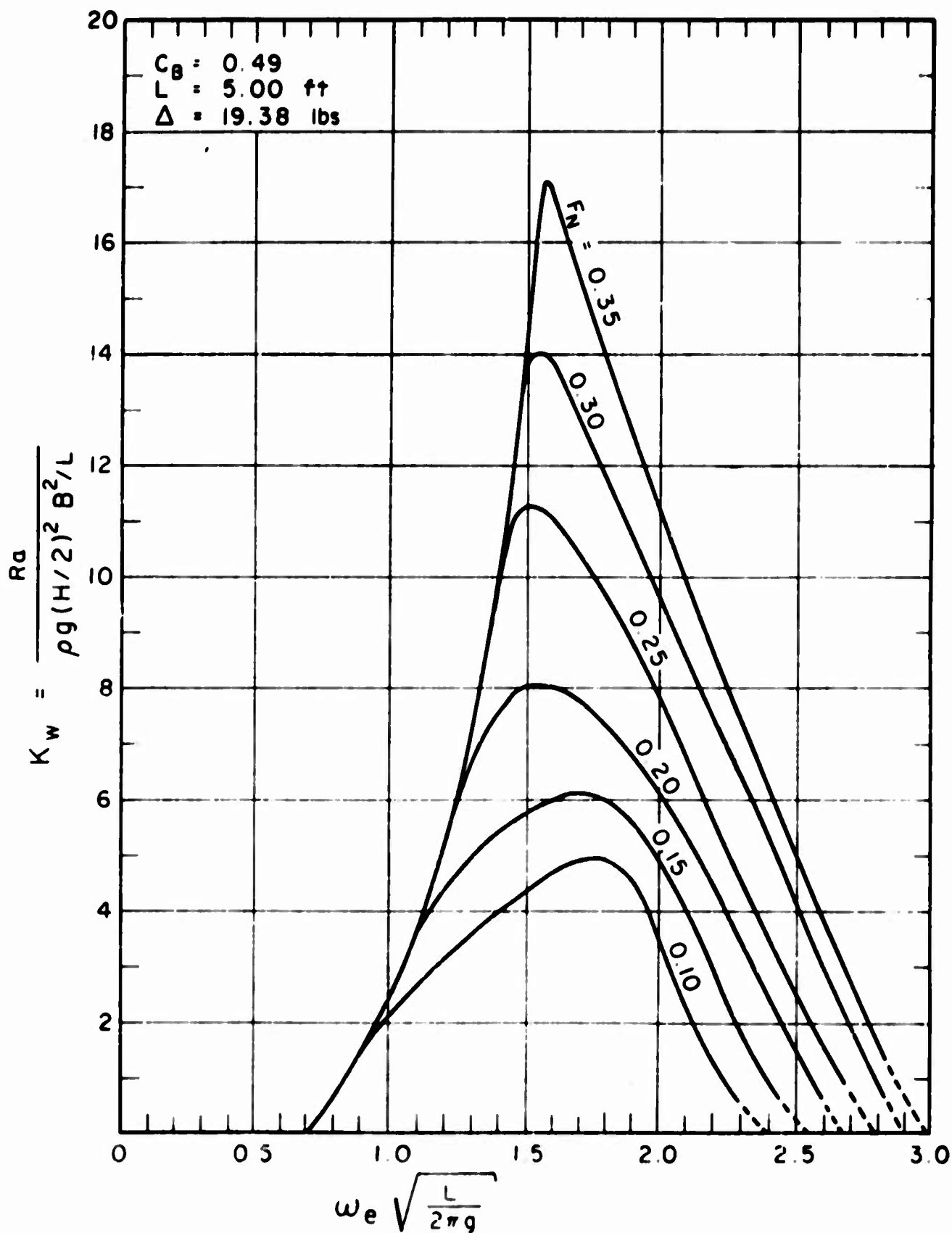FIG. 4   HORIZONTAL DYNAMIC FORCE   VS.   WAVE HEIGHT

FIG. 5 HORIZONTAL DYNAMIC FORCE

FIG 6 ADDED RESISTANCE COEFFICIENT IN WAVES
(CONSTANT THRUST)